Moment-Based Physical Models of Broadband Clutter due to Aggregations of Fish

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LONG-TERM GOALS

Contribute to a new understanding of what fish parameters control mid-frequency (MF; 1-10 kHz) biological clutter, and provide data sets and statistical models for signal-processing algorithm development. These in turn will help to develop a capability to statistically forecast the impact of bioclutter on MF Navy systems.

OBJECTIVES

Develop, and refine/validate with field data, broadband stochastic models of MF clutter due to aggregations of fish based on higher-order statistical measures describable in terms of physical and system parameters. Environmentally, these models would help to provide physics-based estimates of acoustical uncertainty based on biological parameters.

APPROACH

Develop and validate a physics-based statistical modeling approach for treating MF acoustic clutter phenomena due to fish via a combination of theoretical developments and field-data collection/analysis. Knowledge on fish distributions and bioacoustics will be used to identify (and provide data on) the key physical parameters needed both to develop (and validate) the clutter models, and to quantify uncertainty.

Theoretically, we build on recent work at NRL in both clutter-persistence characterization and physics-based probabilistic modeling (Fialkowski and Gauss, 2010). The characterization method estimates clutter persistence over sequential sets of pings of normalized correlator (matched-filter) output, with the goal of stabilizing/minimizing coherent propagation effects and thereby identifying the more significant interferers. The probabilistic model is based on NRL's three-parameter Poisson-Rayleigh

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model that, like the K-type model, provides a physical context for relating the characteristics of data distributions to scatterer attributes (density and relative strength). However, with its extra degree of freedom, the P-R model offers the potential to exploit more information through higher-order (4th and 6th) data moments, and so enhance clutter characterization. The model also offers an advantage over other moment-based clutter characterization methods when deriving statistics over a relatively small range extent with correspondingly small sample distributions, such as spatially variable fish aggregations. The utility of this method is enhanced by the closed-form expressions used to estimate the P-R parameter values from data moments.

Experimentally, this effort leveraged two recent ONR-sponsored experiments in the Gulf of Maine (Sept. 2010 and Sept. 2011), where NRL exploited the broadband capabilities of its MF acoustic system to map out both reverberation and clutter spatially, temporally, and spectrally (Gauss et al., 2009). The 2012 Basic Research Challenge (BRC) field study involved two main acoustical sampling strategies: 1) regional surveys, which produce synoptic "snap-shots" of the fish aggregations, and 2) sequenced signals to observe the temporal evolution of the aggregations. The acoustic measurements were supported by ground truth collected by NOAA fisheries vessels that deployed nets to sample the fish for biological information, and used their traditional HF acoustics to characterize their depth dependence and spatial patchiness. The experiment was conducted in cooperation with another BRC experiment led by Drs. Kelly Benoit-Bird and Dezhang Chu, who have kindly provided biological information to this study. Additionally, sardine aerial surveys provided ground truth assessments on the sardines.

Investigations of fish and fish scattering are conducted in support of both the theoretical and experimental clutter modeling efforts. This includes studies of fish abundances, distributions, schooling characteristics, and other parameters Also, models of scattering from fish schools can be considered the kernels of biological clutter modeling. There are two models covering two different scattering regimes that are being refined. One covers the frequency regime near swimbladder resonance (Feuillade et al., 1996), and the other covers frequencies in the geometric scattering regime above resonance (Love, 1981). Both of these models can help characterize the 1.5-11 kHz scattering encountered during the 2012 BRC experiment, in terms of the ground truth estimates of fish sizes, depths and swimbladder properties.

This effort supports, and is supported by, the high-resolution short-range measurements and assessments by other BRC PIs (led by Dr. Kelly Benoit-Bird, BRC Chief Scientist), and together can provide high-fidelity maps of distributions of swimbladder-bearing fish spatially and temporally for this region and time of year. From these oceanographic assessments, in-situ short-range data, and bioacoustic assessments, the key physical parameters for the statistical clutter models (and so clutter-reduction algorithm development) can be identified.

WORK COMPLETED

This year primarily focused on processing and initial analysis of the acoustic data collected on our west-coast,, summer 2012 cruise. Additionally, we continued our statistical model developments. Recent experimental and modeling results will be presented at the upcoming ASA meeting in San Francisco (Gauss et al., 2013).

2012 cruise overview

Using a dipole source and horizontal line-array receiver towed at ~1.5 m/s from the R/V New Horizon, we made measurements of mid-frequency (1.5–11 kHz) backscattering from aggregations of fish in five shallow-water and shelf-break areas off the coast of Oregon (Astoria Canyon to south of Heceta Bank) between 27 July and 5 August 2012. An overview of our OPAREA and our five acoustic measurement sites is shown in Fig. 1.
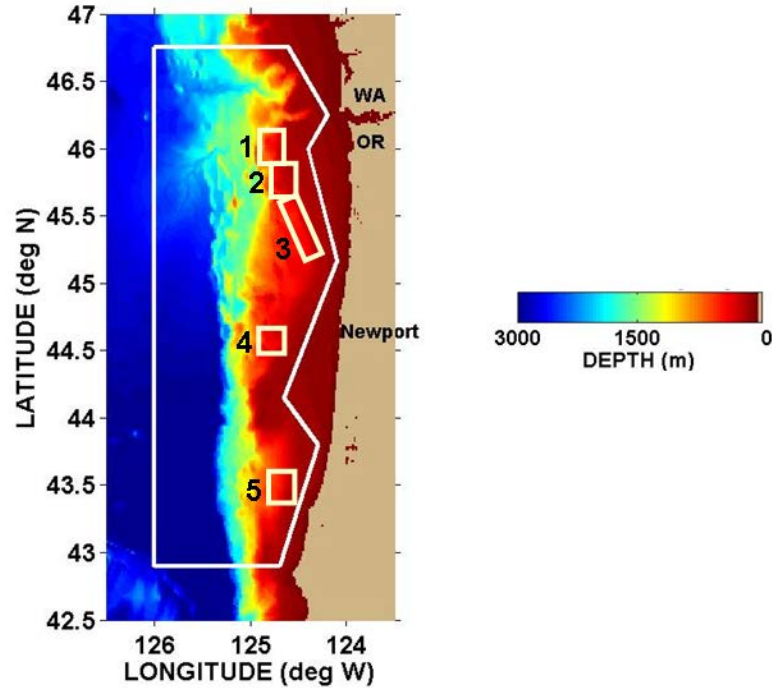

Fig.1. 2012 experimental operating area (white polygon) and the five acoustic measurement sites (boxes) overlain on (NGDC 1-min-resolution) bathymetry.

The environment was oceanographically stable with a downward-refracting sound speed structure (Fig. 2, left) that led to ensonification of the full water column (Fig. 2, right).
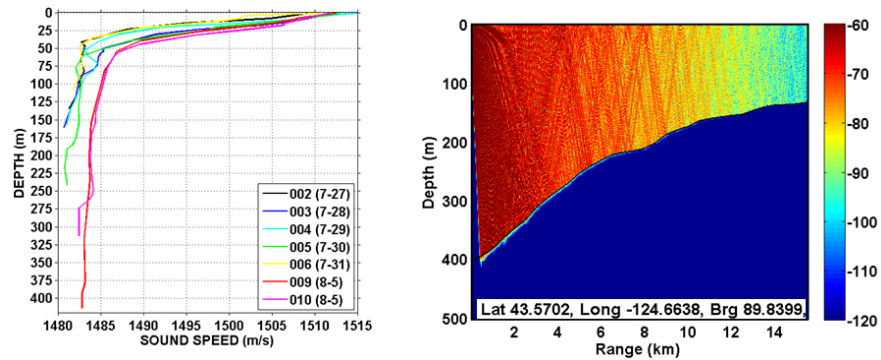

Fig.2. 2012 experimental environment showing representative: (left) sound-speed profiles; and (right) resultant propagation structure via a 4-kHz prediction of transmission loss (source at 20 m).

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FY13 activity has focused on processing acoustic data sets collected using our four primary long-range signals: 4-s upswept, Tukey-shaded FMs with different bandwidths (3.5-5, 1.5-5, 5-9, and 10-11 kHz). The focus of clutter analysis has been on the 3.5-5-kHz FM echo data.

Fish observations

Studies were conducted prior to the 2012 experiment that indicated that Pacific sardines (Love, 2012a) and Pacific hake (Love, 2012b) would be the dominant fish species in the experimental area. This expectation has been affirmed by fishery catch statistics for 2012 (PACFIN, 2013a; PACFIN, 2013b, Hicks et al., 2013). During 2012, sardines accounted 27% of all fish by weight caught off Oregon and Washington and hake accounted for 56%. The size of the sardine stock has been steadily decreasing since 2007 (Hill et al., 2012). The hake stock has been increasing since 2009 (Hicks et al., 2013).

An aerial survey of sardines conducted during August 2012 showed concentrations of sardine schools extending from 47°07.5'N to 44°15'N, with a few schools as far south as 43°15'N. (Jagielo et al., 2012) Although most schools were observed in waters shallower than 200 m, there were several instances where the survey found concentrations of schools well offshore (Fig. 3, left), including in the proximity of one of our acoustic measurements (box 4, Fig. 1). This indicates that, although the NRL acoustic system had to operate off the shelf, the potential for encountering sardine schools existed, especially when the NRL system was looking toward shore.
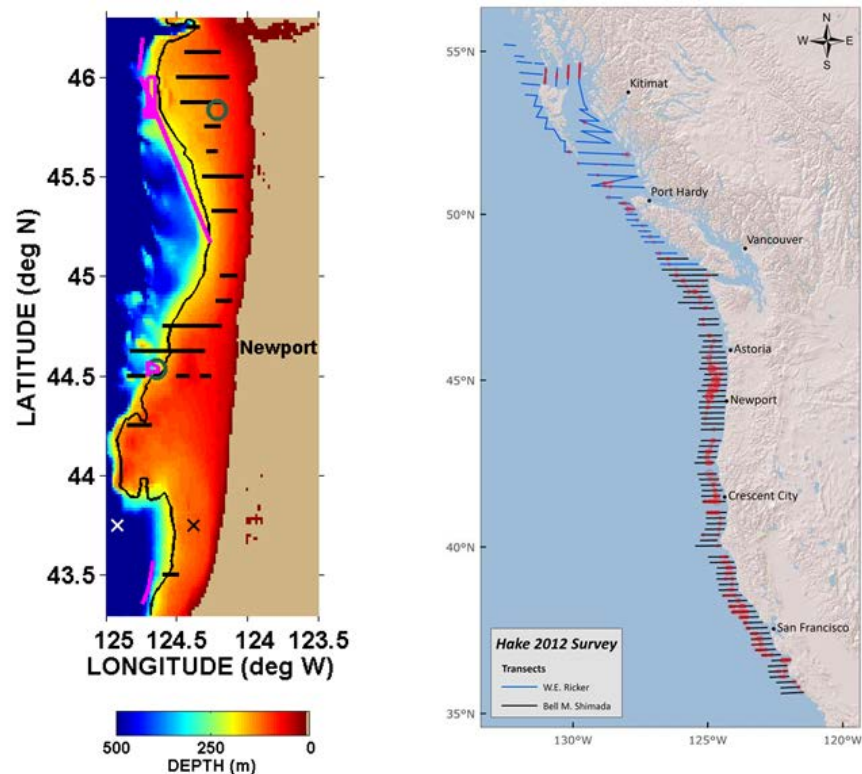

Fig.3. Summer 2012 fish distributions: (left) sardines (aerial survey; Jagielo et al., 2012) overlain on (NGDC 1-min-resolution) bathymetry; and (right) hake (ship-based survey; Hicks et al., 2013)

The depths of sardine schools during the summer off Oregon and Washington are much more restricted than during the winter off California. They are generally between 4 and 15 m deep during the day and descend slightly at night. They disperse somewhat at night but keep some aggregational structure. This was evidenced by nighttime Simrad echo sounding, which frequently showed aggregations in the upper 20 m (Fig. 4, top).
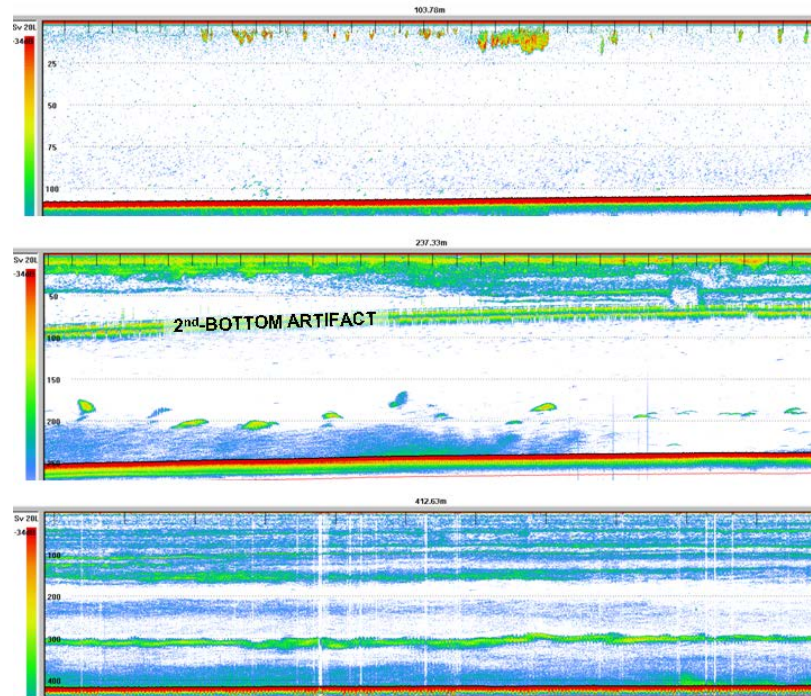

Fig.4. Experimental18-kHz Simrad observations (30-min traces): (top) in shore (~45.8°N; green circle, Fig. 3-left) at night; (middle) west of Arch Cape (~45.9°N' box 2, Fig. 1) in the late afternoon; and (bottom) south of Heceta Bank (~43.4°N; box 5, Fig. 1) during the day. (Note the different depth scales)

There are several other factors of note. During 2012, the equivalent circular diameters of sardine schools ranged from about 10 to 110 m, with almost 40% being between 15 and 25 m. School thicknesses ranged from about 2 m to 13 m, with only a slight increase with school diameter. (Jagielo et al., 2012) Fish in the schools were between about one and two body lengths apart. The mean length of a sardine was 22.5 cm.

A National Marine Fisheries Service survey conducted during the summer of 2012 showed that Pacific hake were concentrated off Oregon (Fig. 3, right). These concentrations extended into areas where NRL was conducting its measurements. However, unlike sardines, hake do not form compact schools. They are generally found in larger, less dense aggregations (as at ~200-m depth in Fig. 4, middle) or layers (as at ~300-m depth in Fig. 4, bottom). Hake aggregations would be expected to produce more extended clutter returns than compact schools of sardines, while layers of hake could produce more reverberation-like returns.

During 2012 over half the Pacific hake were two years old. The median length of a hake was between 42 and 43 cm (Hicks et al., 2013).

Initial acoustic-clutter data-analysis results

Acoustic clutter due to fish depends on the details of: (1) fish distribution (e.g., sizes, depths, and densities); (2) waveguide (e.g., sound-speed field, water depth and bottom properties); (3) sonar (e.g., frequency, source level, and sonar geometry); and (4) signal processing. In this experiment, we had good ground truth on (1) and (2), and had control over (3) and (4) except for environmentally-imposed restrictions: operating area (within the Fig. 1 polygon), source level (< 190 dB), and transmission periods (typically 4 h within a 24-h day). Despite these significant restrictions, high-quality fish-clutter data were collected at all five of our measurement sites (Fig. 1).

Representative examples of normalized match filter data from three of the sites are shown in Fig. 5 for 3.5-5 kHz FM signals. (This signal has a range resolution of 1/1500 m—plotted here are peaks over 200-m range bins.) The spatial echo characteristics vary from compact (b) to extended features (c), with the interplay with the local range-dependent propagation structure also apparrent (most clearly in (a) and (c)). Qualitatively, these spatial characteristics are consistent with those observed concurrently on the Simrad echosounder displays, and so with fish as the source of the clutter-like echoes.
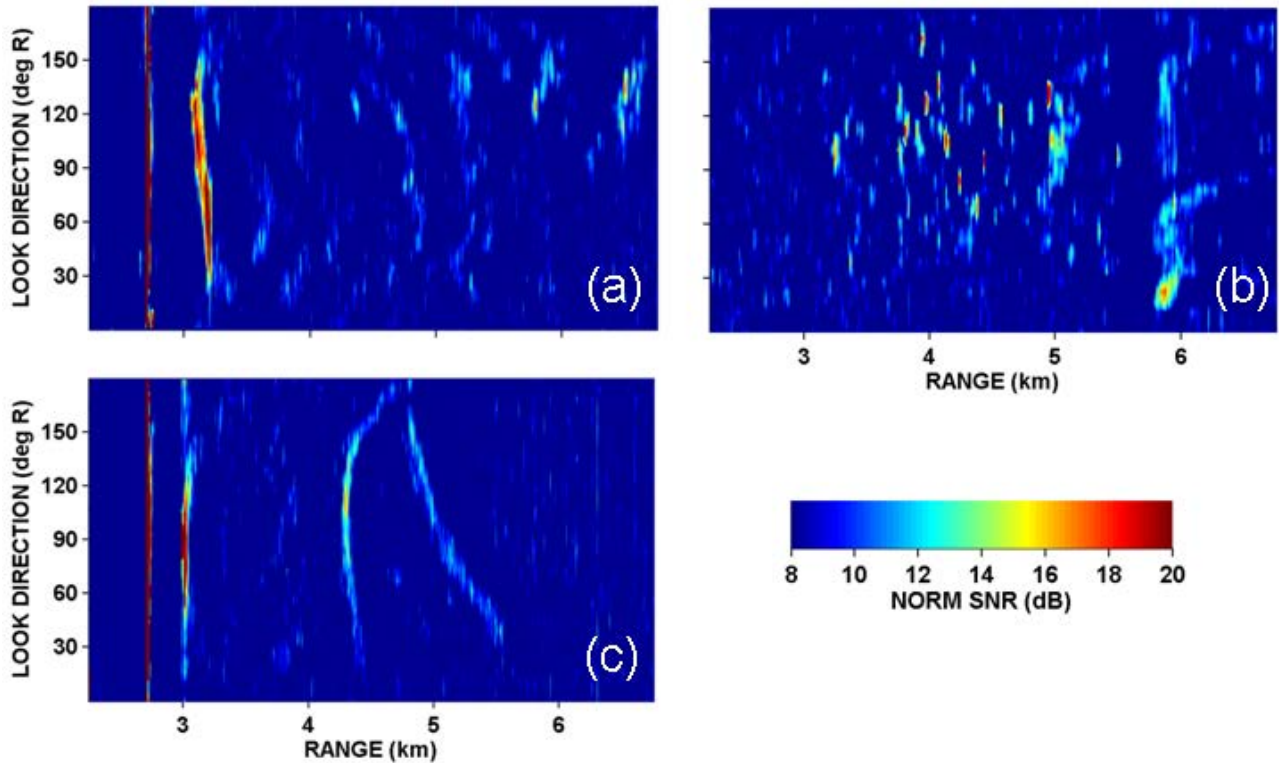

Fig.5. Representative clutter (normalized match-filter) data collected in three geographic areas: (a) Astoria Canyon (~46.1°N; box 1, Fig. 1); (b) north of Heceta Bank (~44.5°N; box 4, Fig. 1); and (c) south of Heceta Bank (~43.4°N; box 5, Fig. 1). (The strong echoes at ~2. 7 and 3.1 s in (a) and (c) are from the direct blast and seafloor respectively.)

Along with clutter's spatial characteristics—do they look target-like?—their temporal characteristics are important in designing robust automated classification and tracking algorithms for MF mobile active sonars that can reduce both their false alarm rate and latency. Accordingly, a quantitative assesment has begun of the temporal persistence of the observed fish-clutter echoes. [While our sonar was moving (slowly at ~1.5 m/s) during transmission and reception, statistically they still provide key information on fish-clutter spatiotemporal variability as would be observed by a mobile active sonar.]

An example of temporal variability from the measurement site north of Heceta Bank (box 4, Fig. 1), where the echoes were both the most intense and spatially the most target like, is shown in Fig. 6. Here we show echoes resulting from four signals transmitted 40 s apart. Qualitatively, it is seen that statistically there is much in common from ping-to-ping, but that there are also notable fluctuations as would be expected with echoes from aggregates of dynamic animals. A temporal persistence method (Fialkowsi and Gauss, 2010) is being applied to quantify these fluctuations.
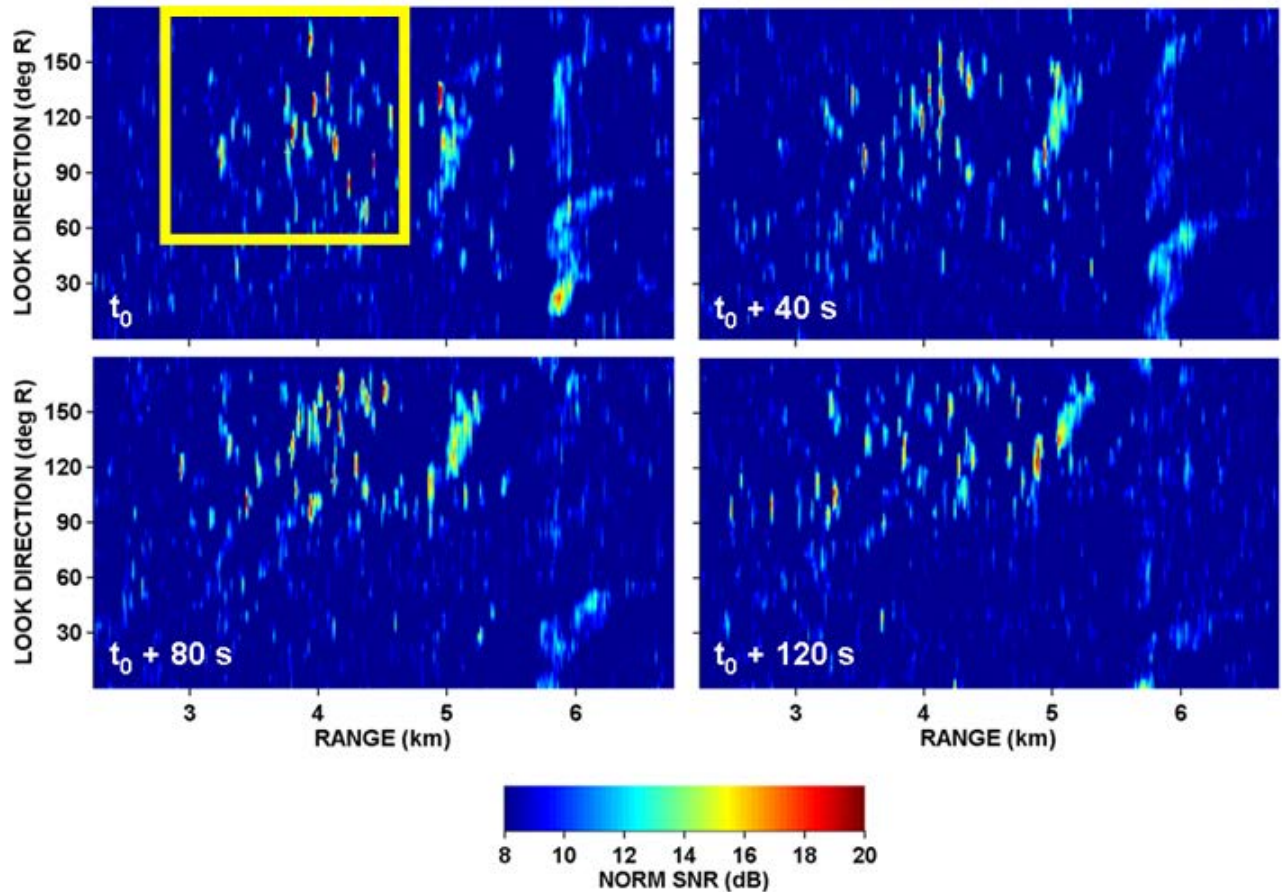

Fig.6. Clutter (normalized match-filter) data from four successive pings (40 s apart) collected north of Heceta Bank (~44.5°N; box 4, Fig. 1).

The acoustic data collected will be used in FY14 to quantify spatial and temporal clutter-echo characteristics, as well any frequency dependence across our 1.5-11 kHz band.

Clutter modeling

In FY12 we developed a new 3-parameter statistical model that not only provides a physical context for relating the characteristics of normalized matched-filter echo-data distributions to scatterer attributes, but scatterer information that is largely independent of its peak signal-to-noise ratio (SNR) value (Gauss and Fialkowski, 2012). It extends our 2-parameter Poisson-Rayleigh (P-R) model by adding a quantitative measure of scatterer spatial uniformity (dispersion) to the P-R model's measures of scatterer density and relative strength. In general, real spatial distributions of geological and biological scatterers can be under-dispersed or over-dispersed. To account for this dispersion, the Conway-Maxwell-Poisson (CMP) distribution was incorporated into our clutter model, so that it is now the 3-parameter CMP-Rayleigh (CMP-R) model.

In FY13, we applied the model to our 2012 normalized matched-filter data, with a representative data-model comparison shown in Fig. 7. In this example, we formed a probability distribution function (PDF) from echoes (peak values non-overlapping 200-m range bins) with at least 12 dB SNR resulting from a single 4-s, 3.5-5–kHz FM transmission that were within a fixed beam-range set (yellow box in Fig. 6). As seen, NRL's CMP-R model fits well the highly non-Rayleigh clutter distribution over the full amplitude range.
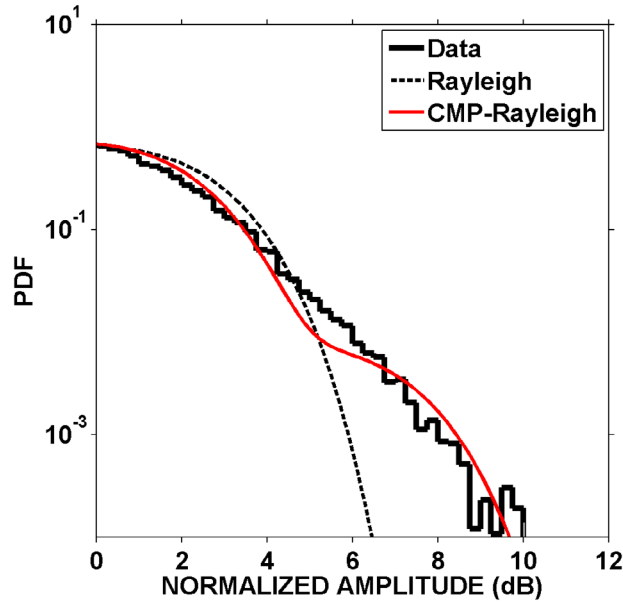

Fig.7. PDF of normalized match-filter data corresponding to the yellow box in Fig. 6 showing the non-Rayleigh character of the data and its matching by the CMP-Rayleigh clutter model.

In FY14, we will quantify the extent to which the CMP-R fish-clutter statistical parameters are consistent with the observed (ground truth) fish-behavior statistics. We will also determine the extent to which these fish clutter echoes might form false targets (Gauss and Fialkowski, 2011).

RESULTS

Analysis to date shows that the echo statistics are consistent with the observed distribution and behavior of the two primary resident fish species (Pacific hake and Pacific sardines): for example, short-time echo variability and spatial patchiness characteristic of the mid-water (hake) and near-surface (sardine) fish that were observed concurrently on echosounder displays. Statistically, the clutter PDFs were found to be non-Rayleigh but well modeled by our CMP-R model that provides a physical context for relating data distributions to scatterer attributes.

IMPACT/APPLICATIONS

Echoes from fish can be the dominant source of reverberation (over the seafloor and sea surface) over a range of important conditions including operational "look" angles, operational frequencies, and operational bandwidths. Reverberation can mask low-to-mid-SNR targets. Moreover, fish echoes often retain coherent structure (i.e., survive the normalization process used by operational Navy active sonars). Coupled with their inherent spatiotemporal variability, fish can be both a significant clutter problem and a prime source of acoustical uncertainty for active sonars. The results of this physics-based effort will advance our understanding of those fish characteristics responsible for sonar clutter, and in turn, will help provide improved clutter models for synthetic trainers, improved clutter management techniques for active clutter discrimination and classification, and improved sonar system performance prediction.

RELATED PROJECTS

Gauss is funded by PEO C4I & Space (PMW 120; Marcus Speckhahn) to help upgrade the Navy's volume scattering strength (VSS) database in littoral waters. The focus of this effort is in support of the Navy's MF active sonars. Under a 6.2 NRL-Base project ending in FY13, Gauss and Fialkowski have developed a physics- and moment-based clutter-rejection technique for improving automated active Navy classifiers that will be under evaluation for transition to the ACB AN/SQQ-89 A(V) 15 system in FY14 under the ONR Active Sonar Automation Enabling Capability Project (Dr. Keith Davidson).

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